Eugene E. Lundquist

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EFFECT OF DEVELOPED WIDTH ON STRENGTH OF AXIALLY LOADED CURVED SHEET STRINGER PANELS

By Albert E. McPherson, Kenneth L. Fienup, and
George Zibritosky
National Bureau of Standards

NACA

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EFFECT OF DEVELOPED WIDTH ON STRENGTH OF AXIALLY LOADED CURVED SHEET STRINGER PANELS

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SUMMARY

Compression tests were made on six 24S-T aluminum alloy curved sheet-stringer panels 12 inches in length and 24 inches in width, reinforced by six Zee stringers spaced 4 inches between centers. The panels had two radii of curvature, 76.5 inches and 25.5 inches, and three sheet thicknesses, 0.025, 0.100, and 0.189 inch. The panels were of the same design as six of the panels of reference 1 except for an increase in developed width from 16 inches to 24 inches.

The increase in developed width had no significant effect on the strain for buckling of sheet between stringers, the strain for buckling of sheet between rivets, the load carried per sheet bay, or the stress at failure; however, it did reduce the critical strain for buckling of the panel as a whole between edge guides.

INTRODUCTION

Comparison of the results of tests of curved panels having three sheet bays with the results of tests of curved panels having only one sheet bay (reference 1) shows that an increase in buckling load of as much as 100 percent may result from the increase from one to three in the number of sheet bays used in the test panel. The present report is intended to answer the question of whether or not a further increase to five sheet bays would cause any further increase in buckling load and also to show whether or not there is a corresponding effect of the number of sheet bays on buckling between rivets, effective width, and strength.

The panels were of the same design as six of the panels of reference 1 except for an increase in developed width from 16 inches to 24 inches.

This investigation, conducted at the National Bureau of Standards, was sponsored by, and conducted with financial assistance from, the National Advisory Committee for Aeronautics.

APPARATUS AND TESTS

Panels. - The dimensions of the panels are given in table 1 and in figure 1. The stringers, the sheet, and the rivets were 24S-T aluminum alloy. The stringers were nominally of the same dimensions for all the panels. Actually their cross-sectional area varied between 0.190 and 0.199 square inch.

The thickness of the sheet in the panels was taken as the average of 10 readings. The variation of sheet thickness in a given panel did not exceed 0.0008 inch. The area of the panel was determined from the weight, density, and length after correcting the weight for the weight of the rivet heads. This area agreed with the area obtained from cross-sectional dimensions within 1/2 percent.

Panels 1, 2, 3, 4, 5, and 6 had nominally the same sheet thickness, stringer spacing, rivet spacing, and curvature as panels 1, 3, 13, 15, 18, and 20, respectively, of reference 1.

Mechanical properties of material. - Sheet and stringer material was the same as that used for the panels of reference 1.

Mechanical properties of the sheet material are given in table 2 and tensile and compressive stress-strain curves are given in figure 2. Figure 3 gives the family A of compressive stress-strain curves for all stringers and the nominal stress-strain curve B used in computations for all panels.

Preparation of panels. - The sheet was rolled to a radius approximating the desired radius of curvature and the panels were fabricated to nominal dimensions by the Naval Aircraft Factory in Philadelphia.

The panels were prepared for test by clamping them in a supporting jig having the correct radius of curvature and grinding the ends flat and parallel.

SR-4 wire strain gages were attached to the stringers with Duco cement and the cement was allowed to dry 1 to 2 days.

Mounting panels in testing machine. - The tests were made in a 2,300,000-pound horizontal Emery testing machine (fig. 4). The panel and its supporting jig were suspended from the top screw of the testing machine with the panel centroid at the center line of the testing machine heads. Ground steel blocks were suspended from the upper screw of the machine and were placed between the ends of the panel and the heads of the testing machine. A plaster cap was then cast between the end block and the movable head of the testing machine at a load of about 300 pounds.

After the plaster cap had set the load was increased to about 1000 pounds, the supporting jig removed, and edge guides attached (fig. 5). The edge guides approximated the support of the sheet at the stringers. They allowed the edge of the sheet to move freely in its own plane, but prevented lateral displacements. Details of construction of these guides are shown in figure 8 of reference 2. Figure 5 shows the edge guides A and end blocks B attached to a panel.

It will be noted that the spacing between the edge guides and the nearest stringer was only 2 inches instead of being equal to the distance of 4 inches between adjacent stringers. This was due to an oversight in the fabrication of the panels. The resulting effect on the load carried by the edge bays was taken into account in the analysis of the data.

The method of suspending the weight of the panel, edge guides, and end blocks from the top screw of the testing machine is shown in figure 4.

Strain measurements. - Twelve 2-inch Tuckerman strain gages were attached to the stringers of the panel (fig. 5). Six of these gages were attached directly to the outstanding flanges. The remaining six gages measured the strain on the stringer flange joined to the sheet using the lever strain transfers described on page 4 of reference 3.

Stringer strains were measured with the Tuckerman strain gages except during buckling, which was sometimes violent enough to throw the Tuckerman strain gages out of adjustment. (See also reference 1.) The change in strain during buckling was measured with two type A-1 SR-4 wire strain gages attached to each stringer of the panel.

Figure 4 shows the method of reading the Tuckerman strain gages, and the strain indicator A and switch B used for measurement of the strain from the 12 wire gages.

Figure 6 shows the location of the strain gages on the stringer cross section. The strain ϵ at the centroid of the stringer and the strain ϵ' at the point of contact of the sheet and the stringer were computed as in reference 1 from the measured strains, on the assumption that the strain in the stringer varied linearly with the distance from the sheet.

Buckling. - The buckling of the sheet between stringers and the twisting of the stringers was noted by frequent visual inspection. The load for buckling of the sheet between rivets was taken as the load at which paper 0.004 inch thick could be slid between the sheet and stringer midway between rivets.

After mounting the panel in the testing machine, the strain was measured for small increments in load. At a load of about 10 percent of the expected maximum load the measured strains were compared to check on the uniformity of load distribution. The strains were found to scatter less than 10 percent from their average value in every case. Loading was therefore continued up to failure.

RESULTS

Strains. - The load-strain graphs are shown in figures 7 to 12. The stringer strains are the strains ϵ at the centroids of the stringers and the sheet strains are the strains ϵ' in the extreme fiber of the stringer at the surface of contact between stringer and sheet.

The increments in strain were taken from the Tuckerman gage readings, except in those cases where the Tuckerman gages were thrown out of adjustment by sudden buckling of the sheet; in such cases the strain increments were taken from readings of the SR-4 wire strain gages.

Buckling. - The strains for buckling of the sheet and for stringer instability are given in table 3. A photograph of the specimens after failure is shown in figure 13. In panels 1, 2, and 3 the sheet buckled between stringers. The first indication of the sheet buckling between stringers for panel 1 was at a load equal to 16 percent of the maximum load and the number of buckles increased until a load equal to 88 percent of the maximum was reached. In panels 3 and 4 buckling between rivets took place at the maximum load. The buckles extended over an area including four stringers. The strains for buckling (table 3) were obtained by extrapolation of the load-strain curve for the sheet at the stringers involved. Panels 5 and 6 buckled as a whole between edge guides. In panel 5 the entire sheet and all of the stringers buckled in a direction away from the axis of curvature of the panel. This was followed by failure due to stringer instability. In panel 6 stringer instability occurred first and was followed by buckling of the panel as a whole; two stringers on each edge and their adjoining sheet area buckled toward the center of curvature of the panel while the center two stringers and their adjoining sheet area buckled away from the center of curvature of the panel.

Failure. - The ultimate load, average stress at failure, average stringer stress at failure, average sheet strain at failure, and type of failure are summarized in table 4.

ANALYSIS

Buckling of sheet between stringers. - Figure 14 shows a dimensionless plot of critical strain for buckling of the sheet between stringers plotted against the curvature for panels 1, 2, and 3 and for panels 1, 3, and 13 of reference 1. Panels 1, 3, and 13 of reference 1 were nominally the same as panels 1, 2, and 3 of the present report except that they were 16 inches in width. The buckling strains for panels 1, 2, and 3 are from 10.4 percent smaller to 9 percent larger than those for the corresponding panels of reference 1. These differences are considered to be within the experimental deviation due to slight variations in curvature.

Leggett's curves, for critical stress (reference 4, fig. 1) are plotted in figure 14 as curve A for clamped support and curve B for simple support for comparison with the observed data. The experimental critical strains for the 24-inch panels are from 0 to 55 percent above Leggett's values for simple support. Buckling loads about half of those given here were reported by Crate and Levin (reference 5). The difference in buckling loads may be ascribed to differences in the edge restraint. The panels of references 5 and 6 differed from the present panels in having the sheet reinforced by stringers only at the edges as compared to the reinforcement by stringers at six intermediate points for the present panels. The much greater stiffness at the edges of a sheet bay in the present tests against transverse displacements in the plane of the sheet would lead to higher buckling loads in the present tests.

Buckling of sheet between rivets. - Table 3 gives strains for buckling of the sheet between rivets of 0.0039 and 0.0028 for panels 3 and 4, respectively. The strains for the corresponding panels of smaller developed width (panels 13 and 15 of reference 1) were 0.0034 and 0.0032. Panel 2 showed no indication of buckling of sheet between rivets, while the corresponding panel of reference 1 buckled at a strain of 0.0045. It was concluded that within the error of measurement the increase in developed width of the panel from 16 to 24 inches had no effect on the critical strain for buckling between rivets.

Sheet load against edge strain. - The load carried by the sheet between stringers was computed by subtracting the stringer loads and the load carried by the two half-width edge bays from the total load and dividing by 5, the number of internal sheet bays. The stringer load was computed from the stringer area, measured strain, and stringer stress-strain curve, figure 3. The load carried by the half-width edge bays after buckling was computed either from Marguerre's formula (reference 1, equation (14)) or from Wenzek's formula (reference 1, equation (15)) for simply supported sheet, choosing the formula which gave the larger effective width.

The load P carried by the sheet between stringers is plotted in dimensionless form Pb/Et^3 against edge strain ratio $\epsilon' b^2/t^2$ in figures 15 and 16. The points are plotted solid for $\epsilon' > 0.003$ to show the effect of yielding of the material. Figure 15 gives the results for panels 1, 3, 5, and panel 1 of reference 1 having a radius of curvature of 76.5 inches, and figure 16 gives the results for panels 2, 4, 6, and panel 3 of reference 1 having a radius of curvature of 25.5 inches.

Marguerre's formula (reference 1, equation (14)) for the effective width of flat sheet with simply supported edges, is plotted in figures 15 and 16 for comparison with the measured loads. Comparison of the points with the curve shows that the observed loads were higher except when $\epsilon' b^2/t^2 < 7$. In this range most of the observed points check the curve. Those points for which yielding started after $\epsilon' b^2/t^2 = 80$ show a tendency to approach Marguerre's curve for larger values of the edge strain ratio $\epsilon' b^2/t^2$.

Comparison of panel 1 of this report with panel 1 of reference 1, figure 15, and comparison of panel 2 of this report with panel 3 of reference 1, figure 16, shows that increasing the width of the panels from 16 inches (panels of reference 1) to 24 inches (panels of present report) has a negligible effect on the load carried in the elastic range. After yielding the agreement is still good for figure 15 but not good for figure 16. The spread in figure 16 after yielding is probably due to the use of a nominal stress-strain curve for the stringers in determing the stringer load. After yielding the error due to using a nominal stress-strain curve would be greatest. Since the sheet has only half the area of the stringers, an error in determining stringer load appears magnified in the sheet load.

The comparison shows, therefore, that within the error of measurement, increasing the developed width from 16 to 24 inches has no effect on the load carried per sheet bay.

Buckling of panel as a whole between edge guides. - Panels 5 and 6 began buckling as a whole between edge guides at strains of 0.0030 and 0.0040, respectively; while panel 18 (reference 1), which had nominally the same dimensions as panel 5 except for a smaller developed width, showed no indication of buckling between edge guides and panel 20 (reference 1), which has nominally the same dimensions as panel 6 except for a smaller developed width, began buckling as a whole between edge guides at a strain of 0.0050.

It follows that the increase in developed width of the panels from 16 inches to 24 inches reduced the critical strain for buckling of the panels as a whole between edge guides.

Strength of panels. - The measured loads at failure are plotted against computed loads in figure 17. The computed loads were obtained from the nomogram for flat 24S-T aluminum alloy panels, figure 56 of reference 2, assuming a stringer stress at failure of 39 ksi. This value of stringer stress is an average for the flat panels of reference 2, which had stringers of the same design as the stringers used in this report.

Figure 17 shows that the measured loads were from 10 percent higher to 9 percent lower than the loads computed from the nomogram in reference 2. Table 4 gives the average stresses at failure for the panels of reference 1 of similar design to the panels of this report, except for developed width. Comparison shows that the stresses at failure for the 24-inch panels of this report were from 7 percent lower to 6 percent higher than the stresses at failure for the comparable 16-inch panels. Within the error of measurement, the developed width of the panel had no effect on the average stress at failure.

National Bureau of Standards,
Washington, D. C., August 8, 1944.

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1. Ramberg, Walter, Levy, Samuel, and Fienup, Kenneth L.: Effect of Curvature on Strength of Axially Loaded Sheet-Stringer Panels. NACA TN No. 944, 1944.

2. Levy, Samuel, McPherson, Albert E., and Ramberg, Walter: Effect of Rivet and Spot-Weld Spacing on the Strength of Axially Loaded Sheet-Stringer Panels of 24S-T Aluminum Alloy. NACA TN No. 856, 1942.

3. Ramberg, Walter, McPherson, Albert E., and Levy, Sam: Compressive Tests of a Monocoque Box. NACA TN No. 721, 1939.

4. Leggett, D. M. A.: The Buckling of a Long Curved Panel Under Axial Compression. R. & M. No. 1899, British A.R.C., 1942.

5. Crate, Harold and Levin, L. Ross: Data on Buckling Strength of Curved Sheet in Compression. NACA ARR No. 3J04, 1943.

Table 1. - Dimensions of Panels

Panel	Radius R (in.)	Cross-sectional area of panel (in.^{2})	Average cross-sectional area of stringer (in.^{2})	Length of panel l (in.)	Developed width of panel 6b (in.)	Thickness of sheet t (in.)	Rivet spacing L (in.)	b/t	L/t	b^2/Rt
1	76.5	1.778	0.197	11.97	24.05	0.0248	0.50	161.	20.2	8.44
2	25.5	1.750	0.194	11.97	24.02	0.0245	0.50	163.	20.4	25.60
3	76.5	3.610	0.199	11.97	24.07	0.1003	1.50	39.9	15.0	2.09
4	25.5	3.553	0.192	11.98	24.10	0.0997	1.50	40.1	15.0	6.29
5	76.5	5.717	0.194	11.98	24.09	0.189	1.50	21.2	7.9	1.11
6	25.5	5.700	0.190	11.96	24.16	0.189	1.50	21.2	7.9	3.32

Table 2. Tensile and Compressive Properties of Sheet

Nominal thickness of sheet (in.)	Direction of load	Young's modulus		Yield strength		Tensile strength ksi
		Tension ksi	Compression ksi	Tension ksi	Compression ksi	
0.025	longitudinal	10,500	10,700	48.3	42.0	65.2
.025	transverse	10,600	--	44.1	--	65.7
.100	longitudinal	10,400	10,500	58.5	47.5	73.7
.100	transverse	10,300	--	49.2	--	71.5
.188	longitudinal	10,400	10,500	54.5	44.8	72.0
.188	transverse	10,500	--	47.0	--	69.0

Table 3.- Strain for Buckling of Sheet and Instability of Stringers

Panel	Buckling of sheet between stringers	Buckling of sheet between rivets	Instability of stringer	Buckling of panel as a whole between edge guides
1	.0004	--	.0041	--
2	.0008	--	.00375	--
3	.0027	.0039*	.00325	--
4	--	.0028*	.0033	--
5	--	--	.0035	.0030
6	--	--	.0034	.0040

* Extrapolated from load strain curve

-- No buckling

Table 4.- Failure of Panels

Panel	Maximum load P (kips)	Stress (average) P/A ksi	Stringer stress (average) (extrapolated) σ_{st} ksi	Sheet strain (average) (extrapolated) ϵ'	P/A for panel of similar design width = 16" (reference 1)	Type of failure
1	57.0	32.1	39.2	.0054	31.0	stringer instability
2	55.5	31.7	37.7	.0050	30.0	stringer instability
3	123.0	34.1	37.2	.0045	32.9	stringer instability
4	123.7	34.8	34.0	.0032	34.7	stringer instability*
5	192.8	33.7	40.0	.0029	36.4	stringer instability
6	232.6	40.8	37.5	.0043	40.7	Buckling between edge guides.

* Change of buckle pattern at failure

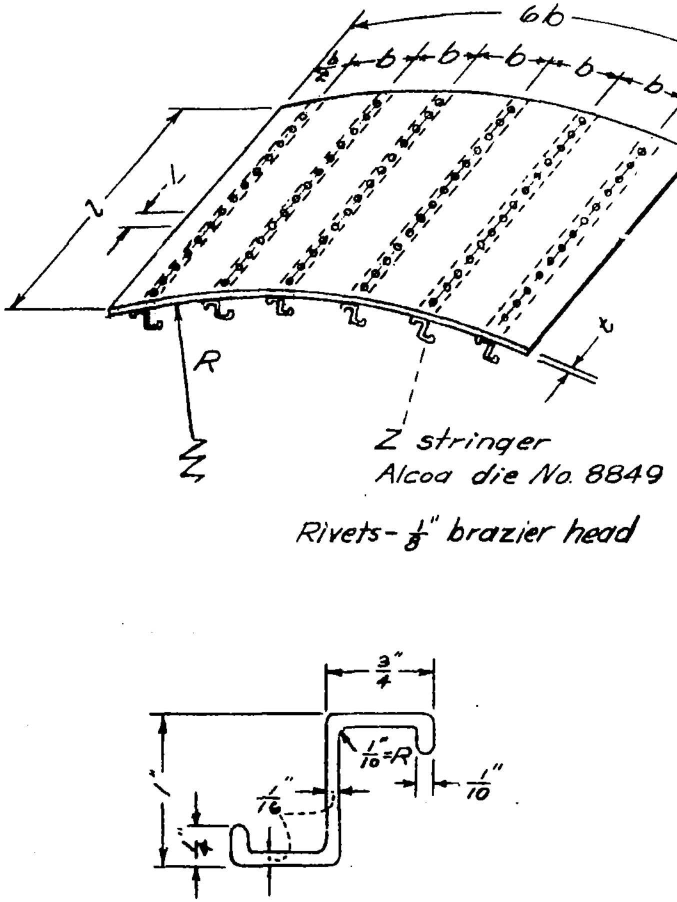

Figure 1.- Panel and stringer dimensions.

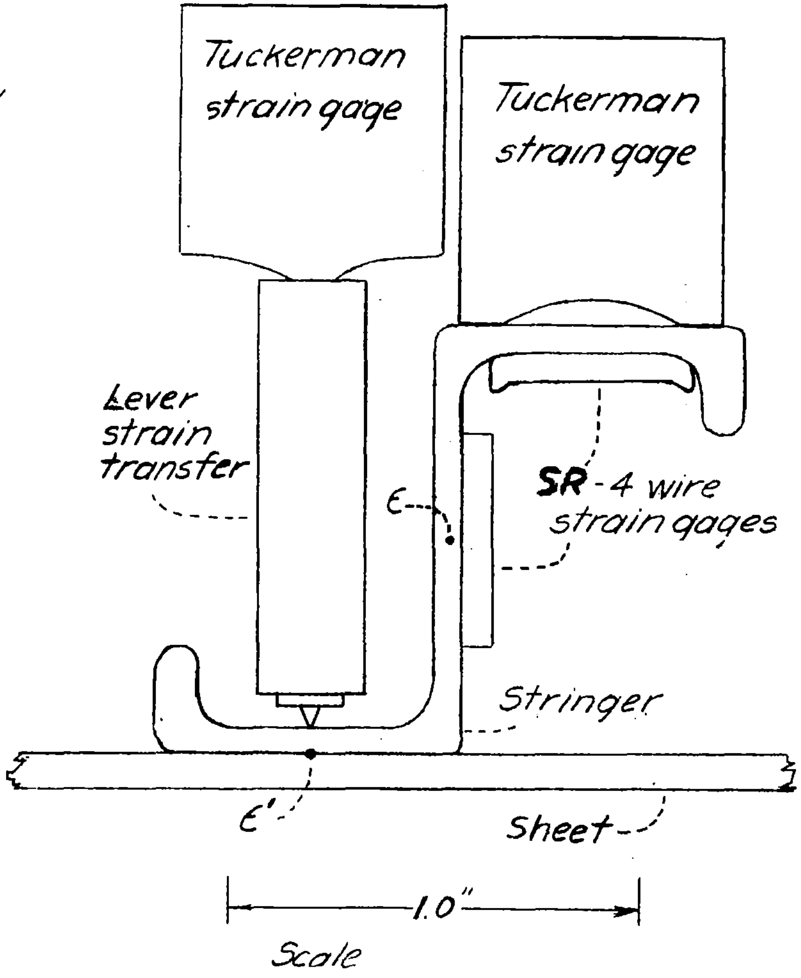

Figure 6.- Location of strain gages on stringer cross-section.

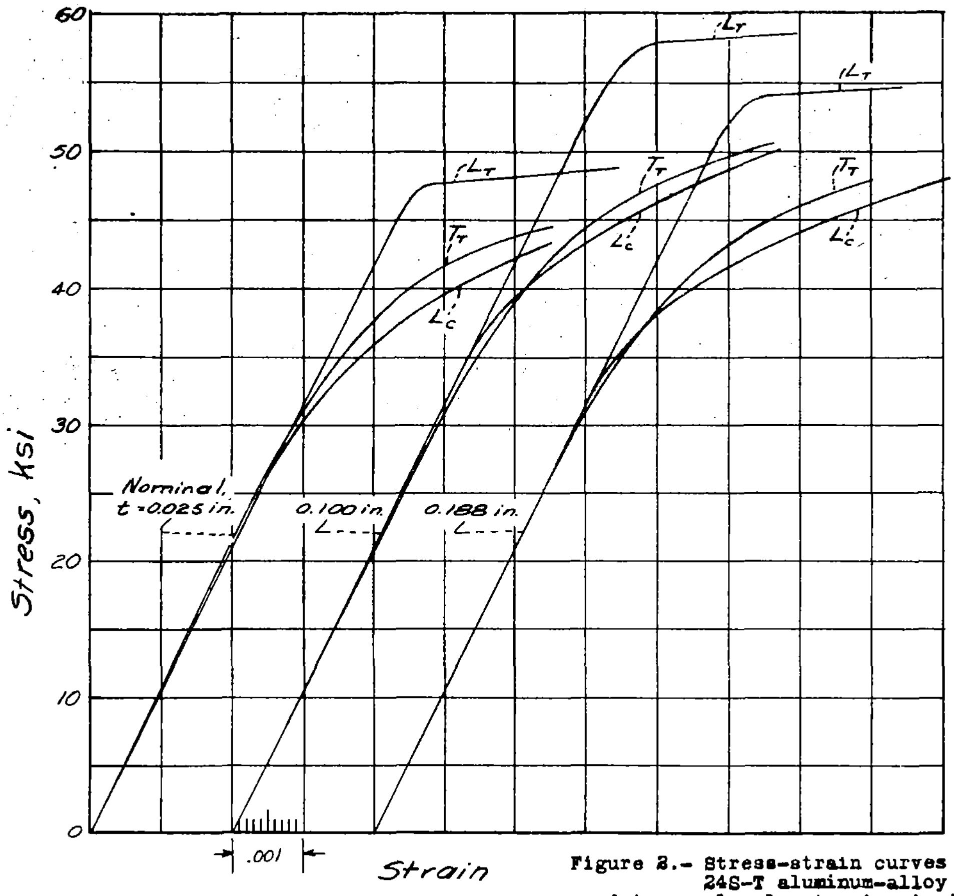

Figure 2.- Stress-strain curves of 24S-T aluminum-alloy sheet used in panels. L_t, tension in direction of rolling; L_c, compression in direction of rolling; T_t, tension transverse to direction of rolling.

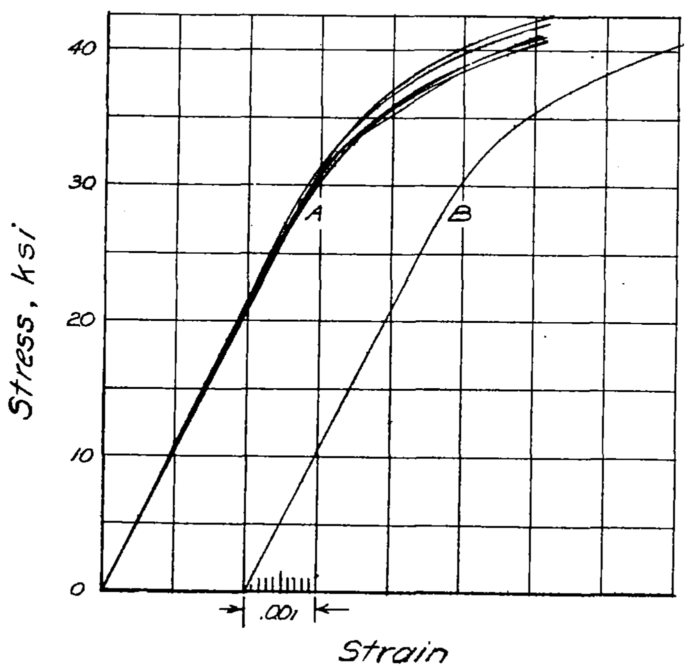

Figure 3.- Compressive stress-strain curves of four-inch lengths of Z-stringers; A, family of stress-strain curves for all the stringers; B, nominal stress-strain curve used in computations for all panels.

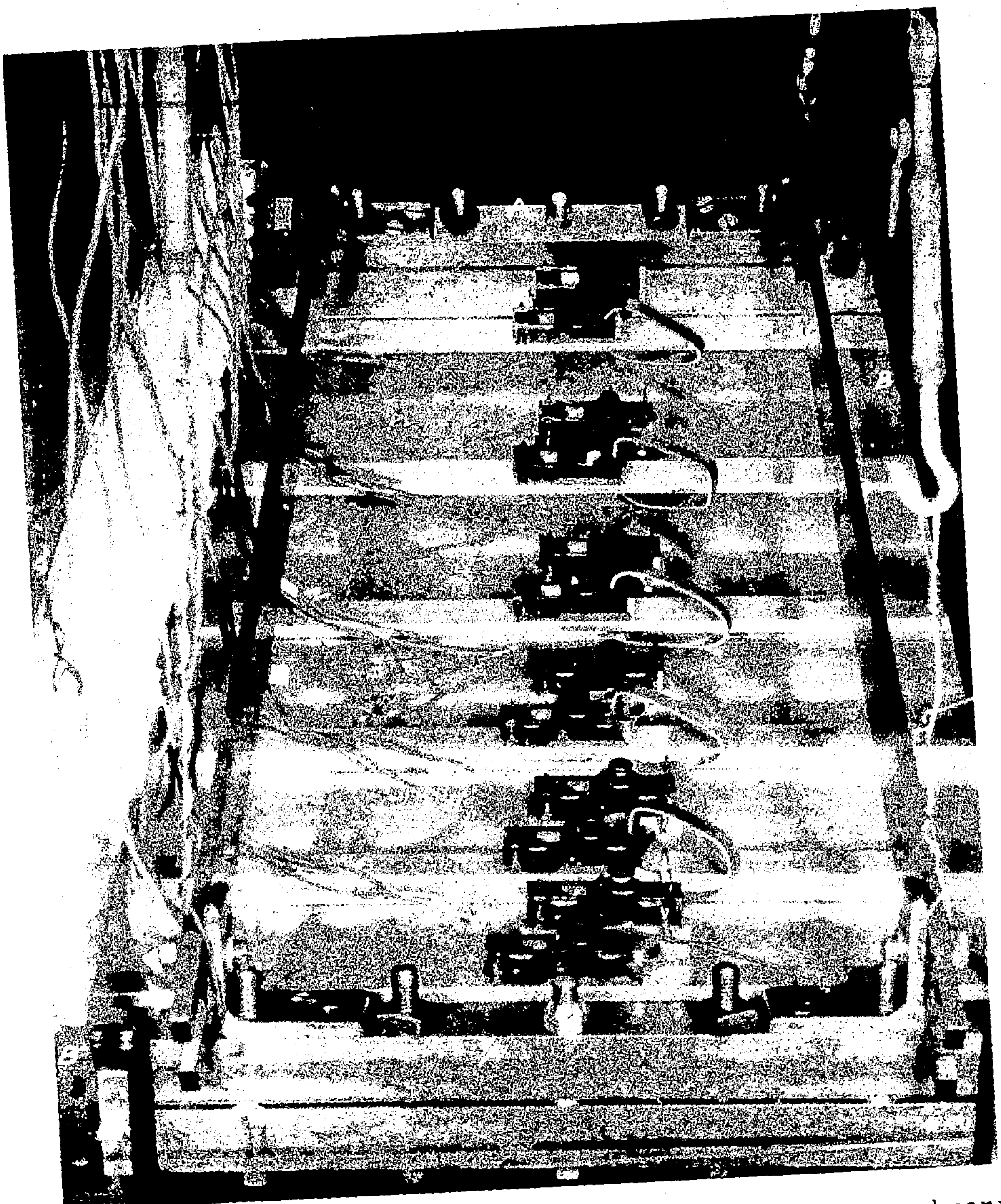

Figure 5.- Panel 4 during test showing wire gage attachment and edge guide detail.

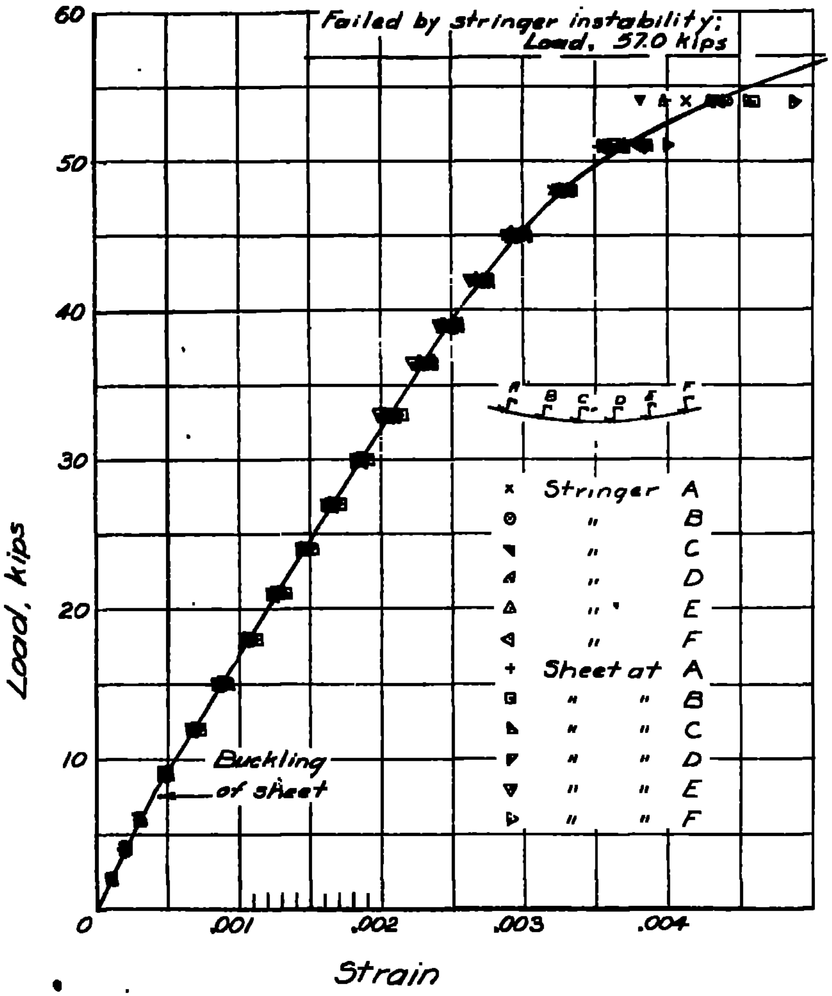

Figure 7.- Test of panel 1; radius, 76.5 inches. (SR-4 gages used after 48 kips.)

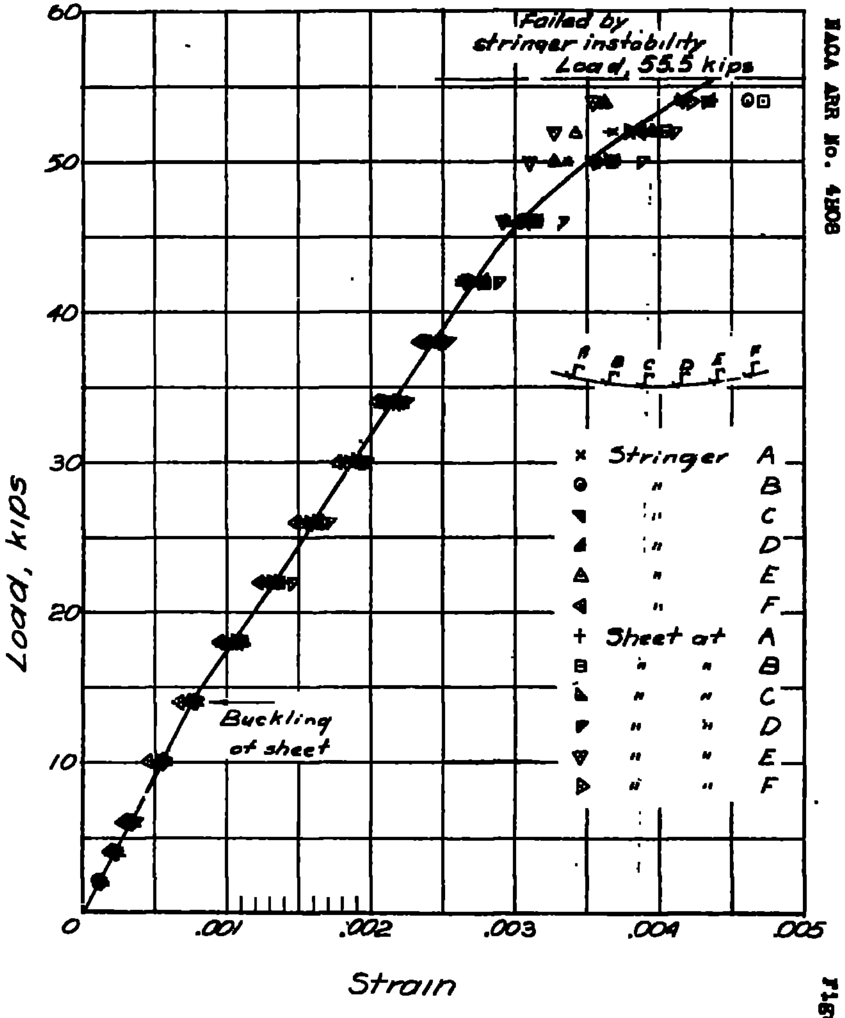

Figure 8.- Test of panel 2; radius, 25.5 inches. (SR-4 gages used after 40 kips.)

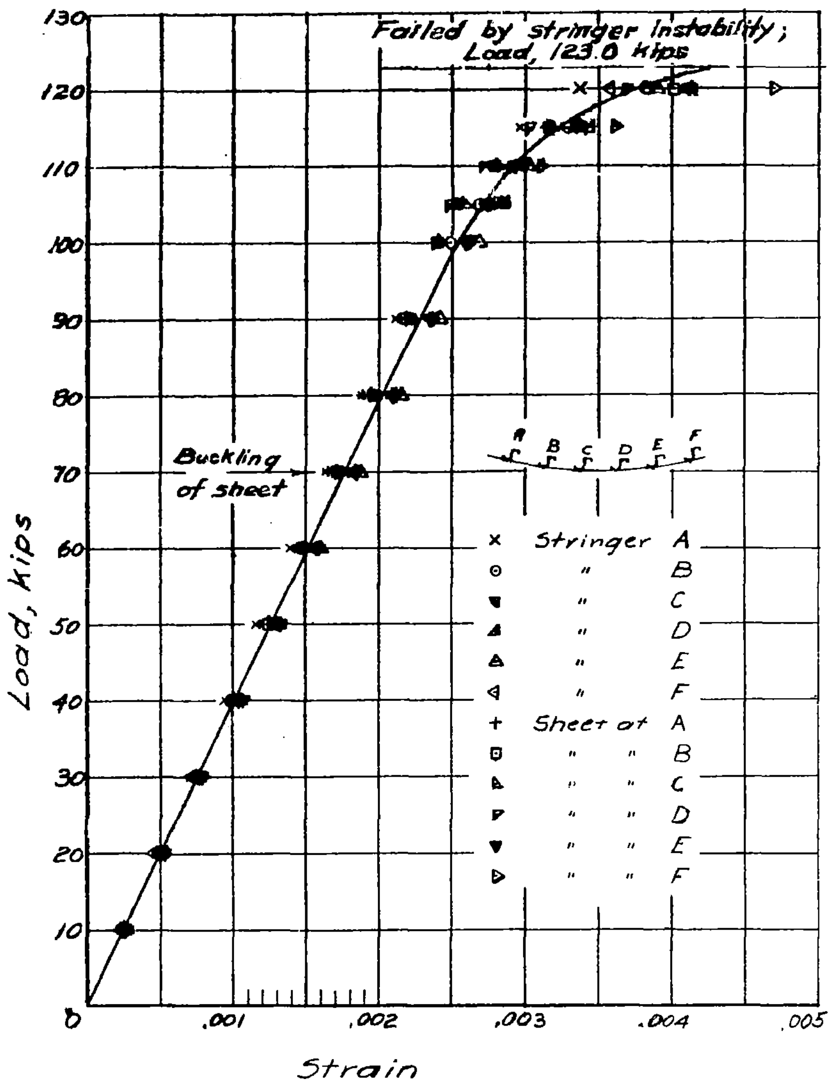

Figure 9.- Test of panel 3; radius, 76.5 inches.

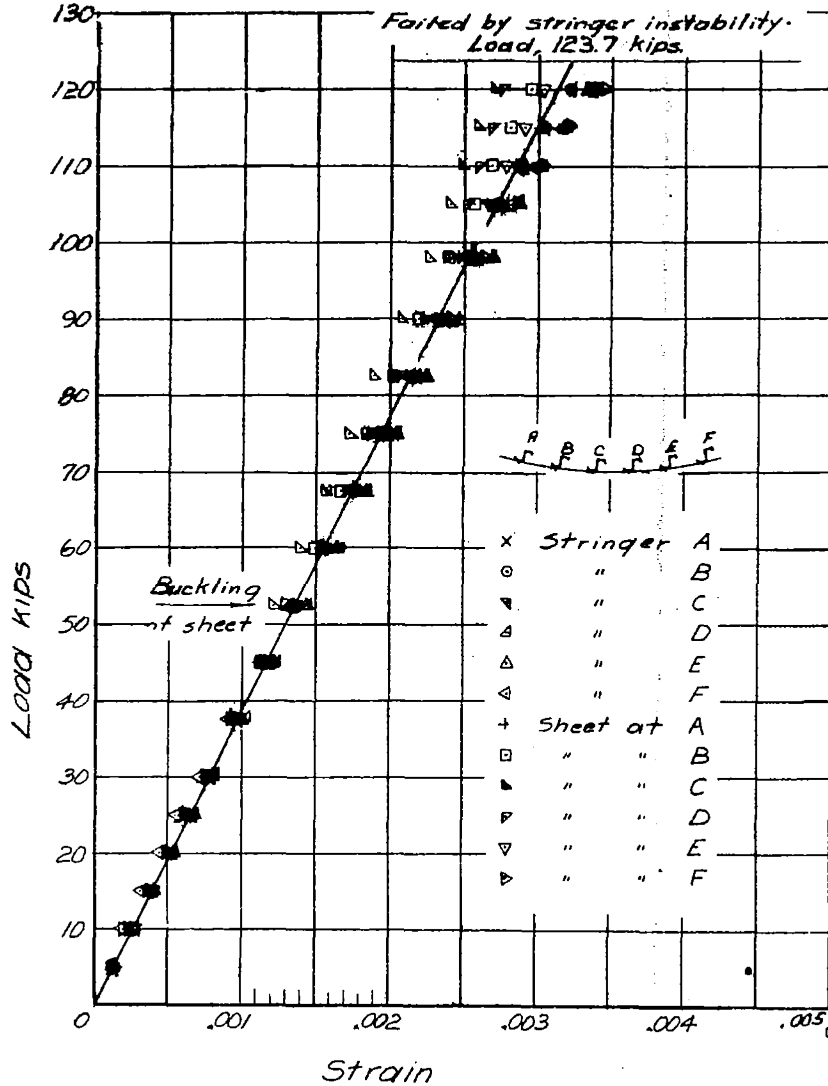

Figure 10.- Test of panel 4; radius, 25.5 inches.

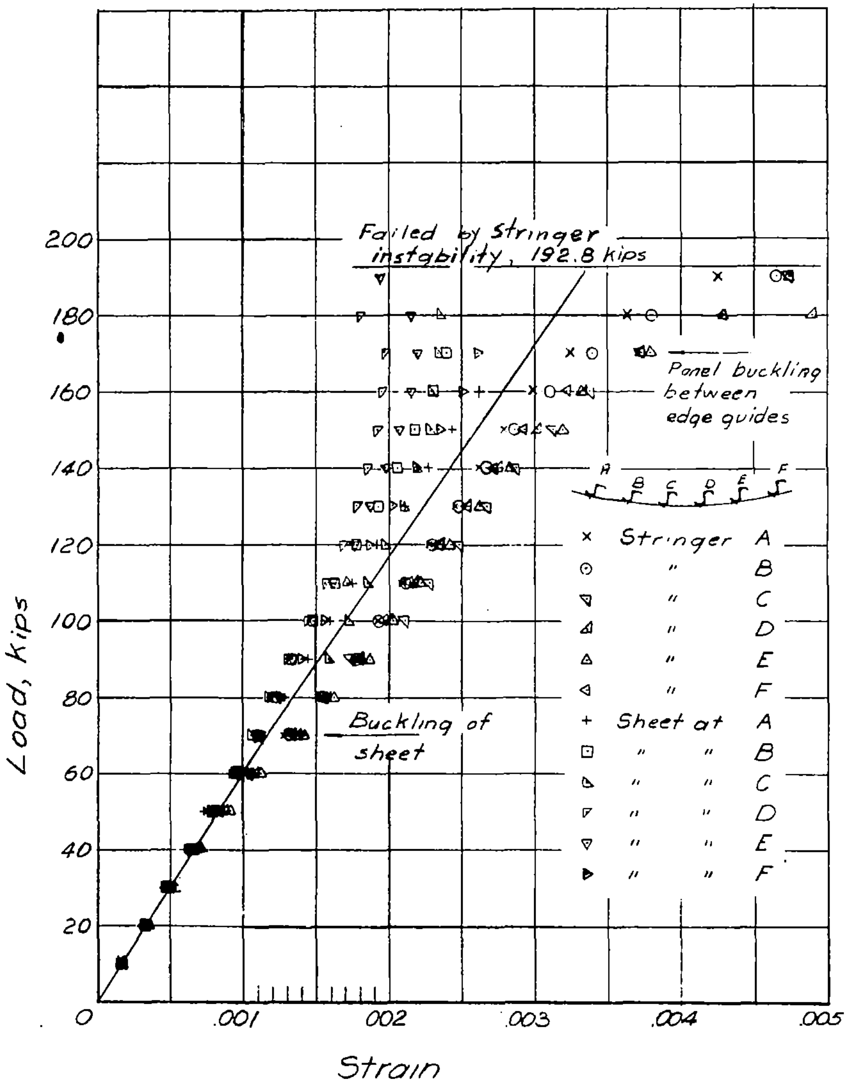

Figure 11.- Test of panel 5; radius, 76.5 inches.

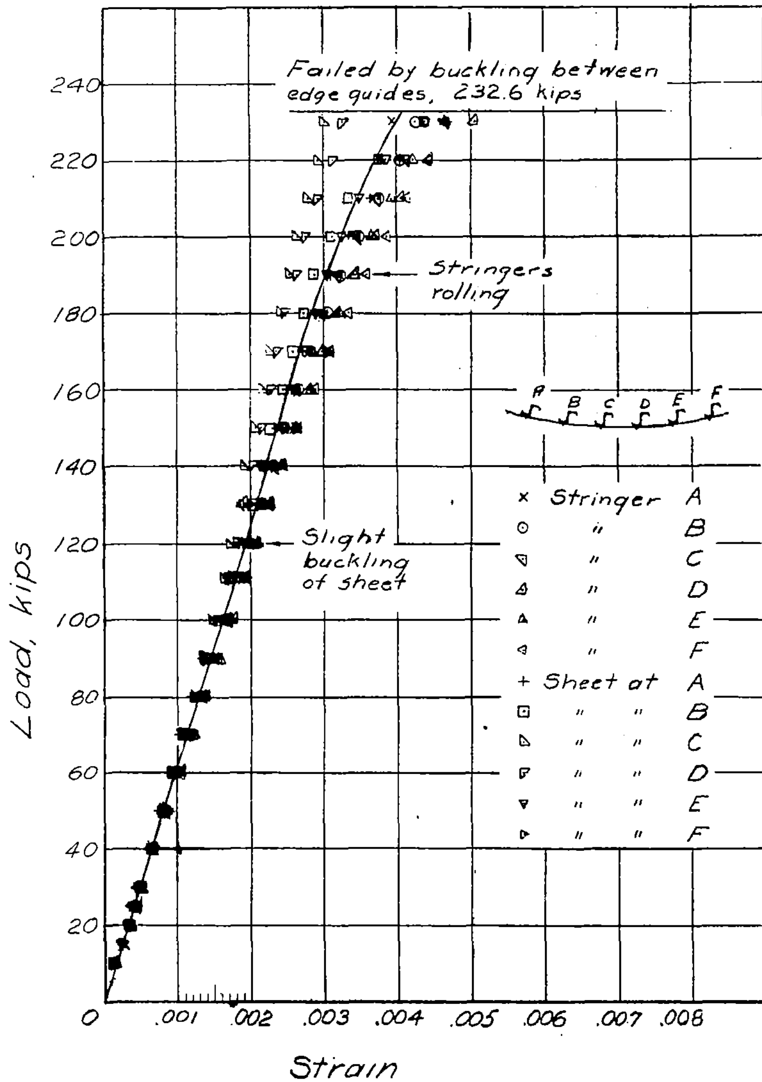

Figure 12.- Test of panel 6; radius, 25.5 inches.

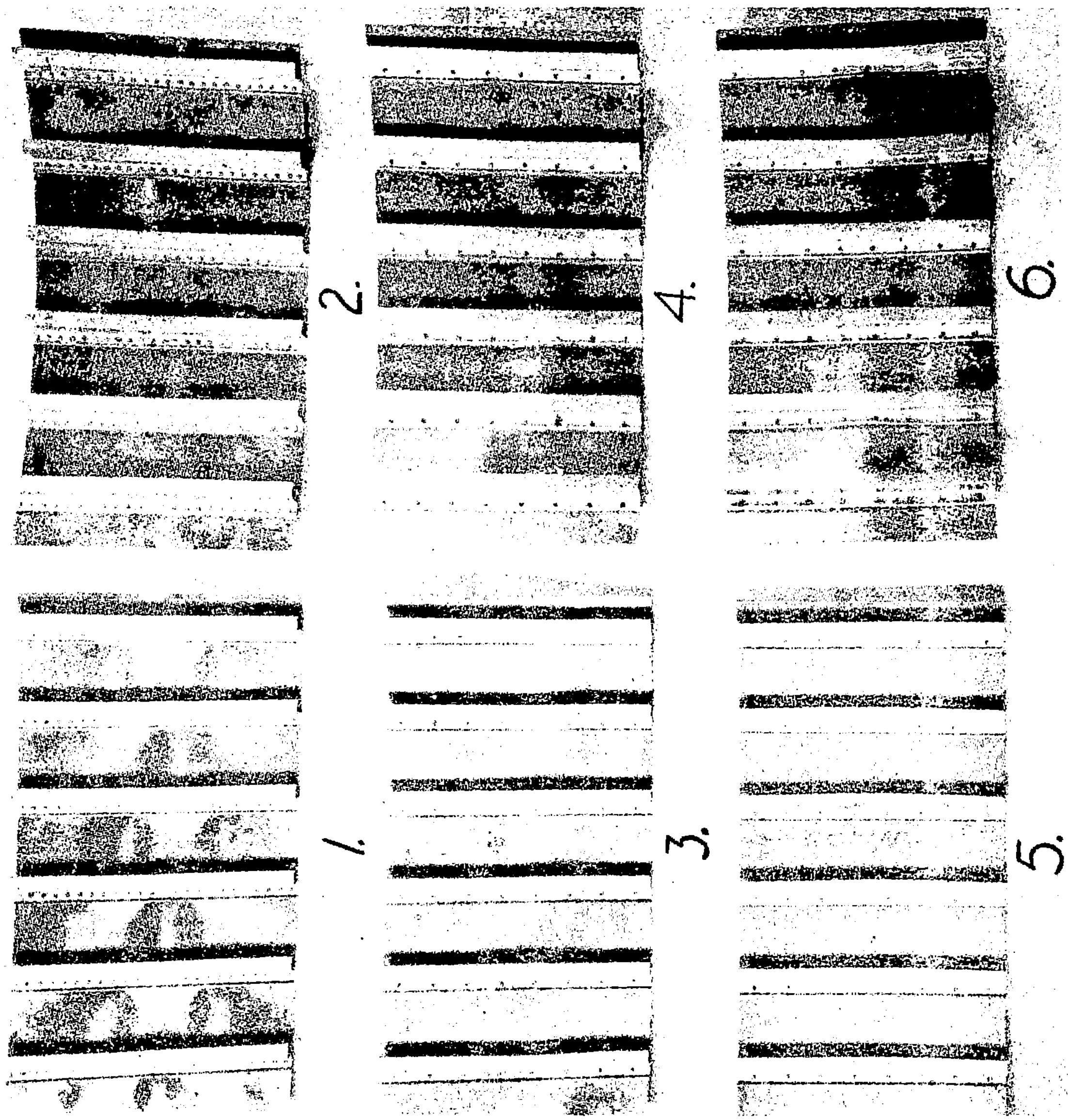

Figure 13.- Panels after failure.

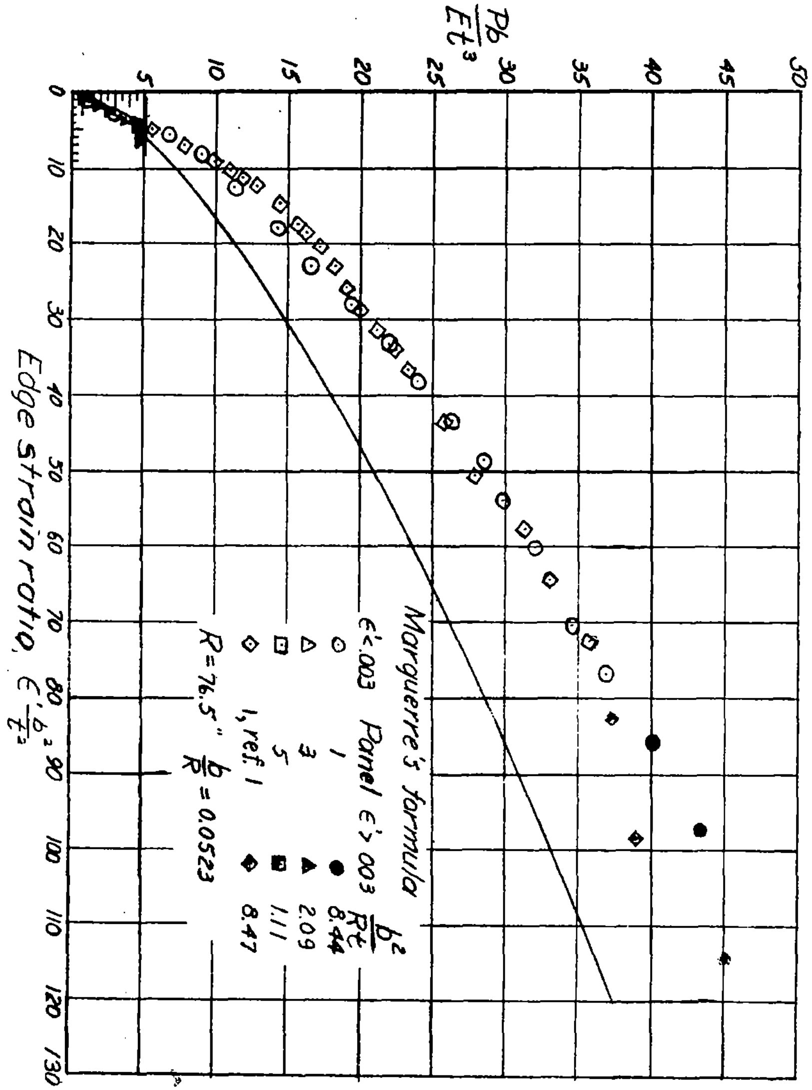

Figure 15.- Load per sheet bay against edge strain: radius, 76.5 inches.

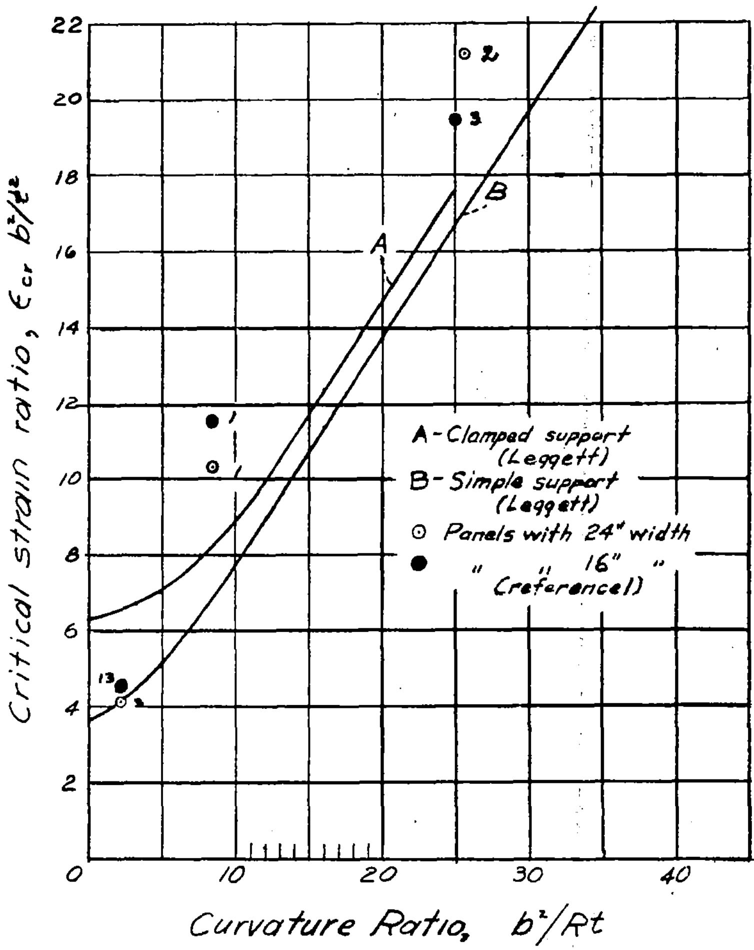

Figure 14.- Critical strain for buckling of curved sheet between stringers.

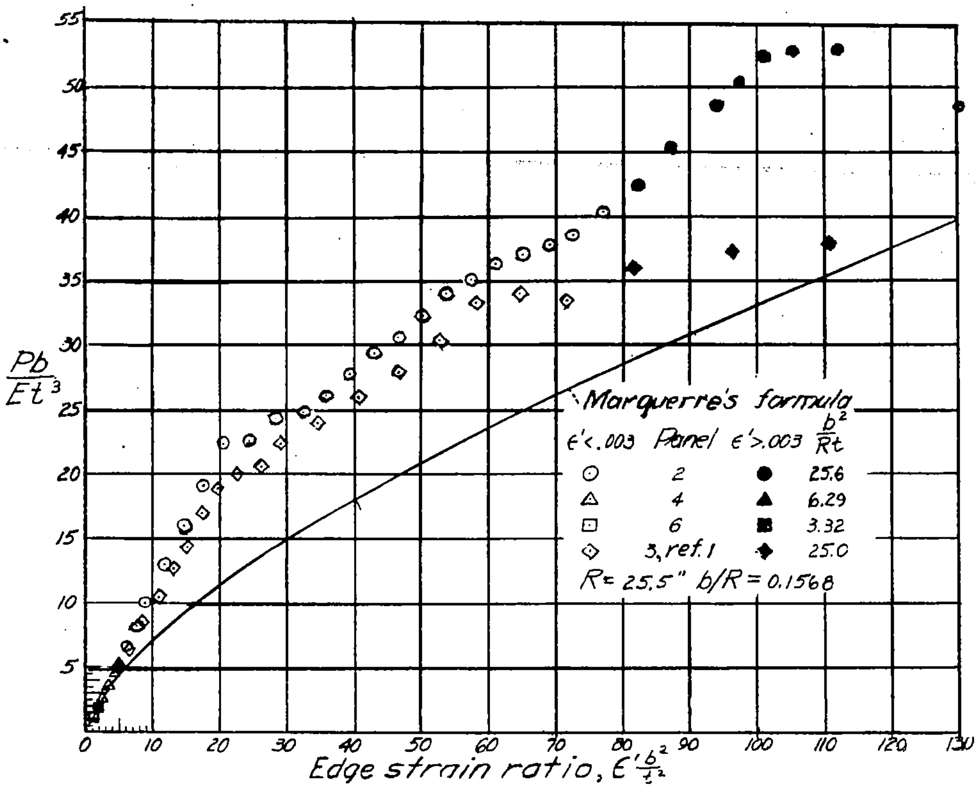

Figure 16.- Load per sheet bay against edge strain; radius, 25.5 inches.

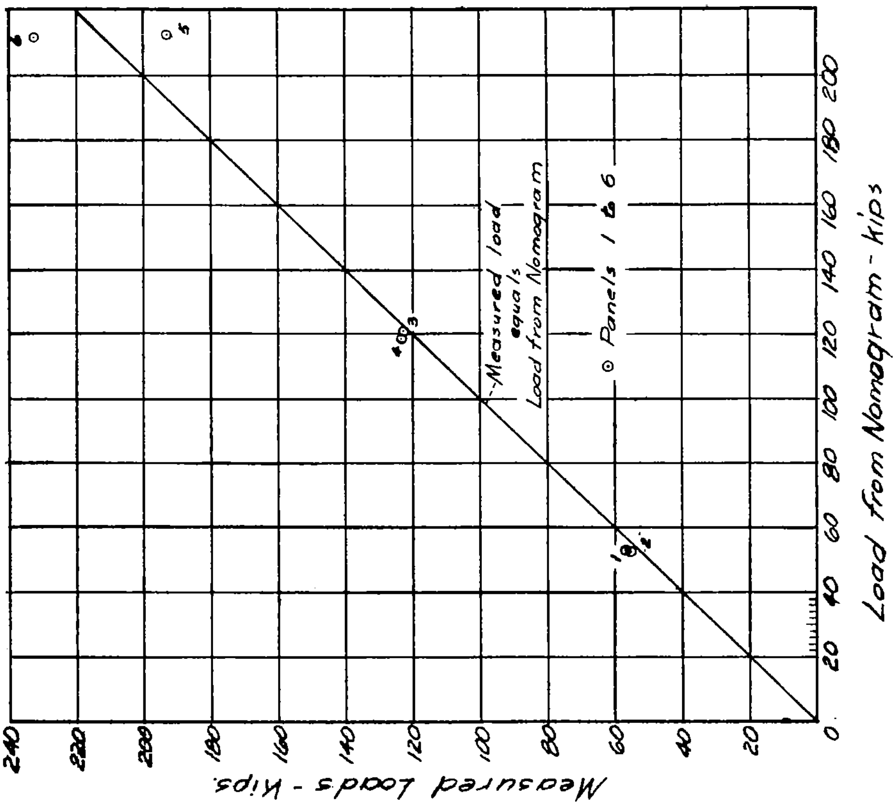

Figure 17.- Measured loads at failure against loads given by nomogram (reference 2).